Wernher von Braun

The Reusable Space Transport

The versatile space shuttle, to be developed over the next ten years, will be the key to the continuing exploration and use of space

The key to future exploration and use of space is the reusable earth-to-orbit transport system. Popularly known as the space shuttle, largely for its logistics application, this vehicle represents a significant new operational capability rather than a discrete mission or missions. Its ultimate impact will be to expand space activity while at the same time reducing the high costs of the space effort, which extend from design and test to flight operations. The shuttle is not a traditional manned vehicle, even though men will fly it. It combines in one transport the capability to launch or carry out unmanned or manned missions repeatedly and routinely. It will be the first true "aerospace" vehicle in that it can fly and maneuver in both space and the atmosphere.

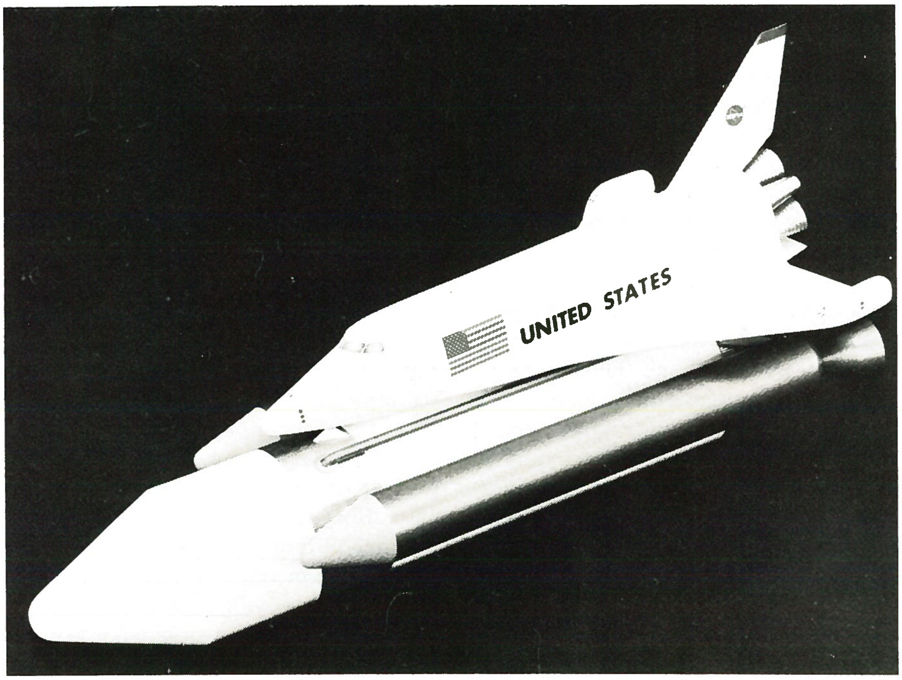

Figure 1. The basic space shuttle design selected by NASA. The orbiter is mounted on a large, expendable liquid hydrogen/oxygen propellant tank with two recoverable and reusable solid propellant motors attached on either side. The complete shuttle is planned to be operational before 1980.

The economy of the shuttle will not depend upon how much hardware it transports *up;* it will depend upon how much it transports up *and* down. Additionally, by relaxing weight and volume constraints now rigidly imposed by current rocket technology, and by giving us the ability to retrieve spacecraft and their payloads in the event of a malfunction or other anomaly, it will make possible economies in the design and fabrication of unmanned spacecraft and their payloads, as well as in the development and test of systems and subsystems.

Dr. Wernher von Braun retired on July 1, 1972, as Deputy Associate Administrator of the National Aeronautics and Space Administration and joined Fairchild Industries as Corporate Vice-President for Engineering and Development. As Director, first, of the Army's missile program and, then, from 1960 to 1970, of NASA's George C. Marshall Space Flight Center, Dr. von Braun guided the development of the series of rockets that placed man in suborbital flight, in orbit around the earth and, finally, on the moon. Under Dr. von Braun's directorship, the Marshall Center also undertook development of the Skylab, Apollo Telescope Mount, Lunar Roving Vehicle, and Shuttle projects. In 1970, Dr. von Braun transferred to NASA headquarters, where he was in charge of planning. He is the recipient of numerous awards and honorary degrees and is the author of many books. A revised edition of Space Frontier *will be published soon by Holt, Rinehart, and Winston. Address: Fairchild Industries, Inc., Sherman Fairchild Technology Center, Fairchild Drive, Germantown, MD 20767.*

More than any previous rocket vehicle, the space shuttle will contribute to progress in NASA's overall program objectives. These include advancing (1) technologies and capabilities for space flight and exploration; (2) space science and study of aerospace phenomena; and, (3) expanded utilization of space and space technology for human benefit.

To achieve the smoothest, most economical progress and benefits at lowest cost to the taxpayers, all three objectives should go forward in fairly close concert, not piecemeal or with fluctuating budgetary peaks and valleys. Our present budget planning is geared to attain this stability over the coming years at about the current annual level of $3.4 billion in 1972 dollars. It is felt that better planning by both NASA and industry will stabilize the national investment in aerospace activities at a more or less constant annual budget figure, and in addition the employment of aerospace personnel can be steadied with consequent steadying of the economy.

The shuttle will replace the various kinds of rocket launchers and facilities, thus drastically reducing the costs of flight operations, spacecraft, and payloads through simplified design, lower launch risk, and reusability. Routine reusability and an orbiter life of 10 years are significant characteristics of shuttle design.

Shuttle design and use

Space shuttle configuration has not yet been completely determined and will depend on refinements to be made as engineering work proceeds. The present concept, shown in Figure 1, is generally representative, differing from the earlier, fully reusable space shuttle (Fig. 2) in the booster stage and in the large external propellants tank attached to the orbiter. In the present concept, the shuttle system consists of four elements clustered together: the orbiter, expendable propellants tank, and twin recoverable solid rocket motors. At launch, the twin motors are ignited simultaneously with the liquid hydrogen/oxygen engines in the orbiter and burn simultaneously with them to an altitude of about 40 km. The solid rockets then detach and descend by parachute, to be recovered, refurbished, and reused at least 10 times.

The orbiter, meanwhile, using its three high-pressure engines, each producing a vacuum thrust of 2,105,600 newtons, continues on to an orbital altitude of 180 km (Fig. 3). There, the large tank is jettisoned, deorbited by retrorockets, and expended in a remote ocean area.

Changes from the original, fully reusable shuttle concept were dictated by both technical considerations and budgetary constraints anticipated for this decade. Development costs would have mounted to $10 billion over a period of six years. Also, NASA would have been developing two hypersonic vehicle programs simultaneously. The present plan, using recoverable solid rockets, will cost $5.1 billion over the same period and represents a much lower technical risk. Part of the saving, of course, will be diminished by the increased cost per shuttle flight, rising from about $5 million in the fully reusable vehicle to $10 million in the current version.

As presently conceived, the shuttle will be used in three distinct modes:

1. To transport unmanned planetary

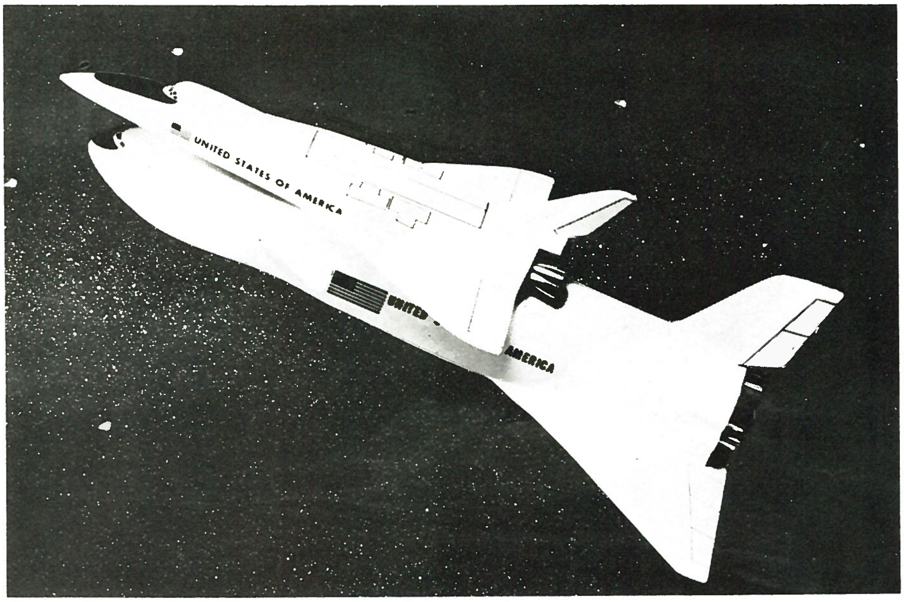

Figure 2. The original, fully reusable space shuttle included a manned booster that would be flown back to base while the orbiter continued on to complete its mission and return in similar fashion. This design has been deemed too technically complex and too costly for development at this time.

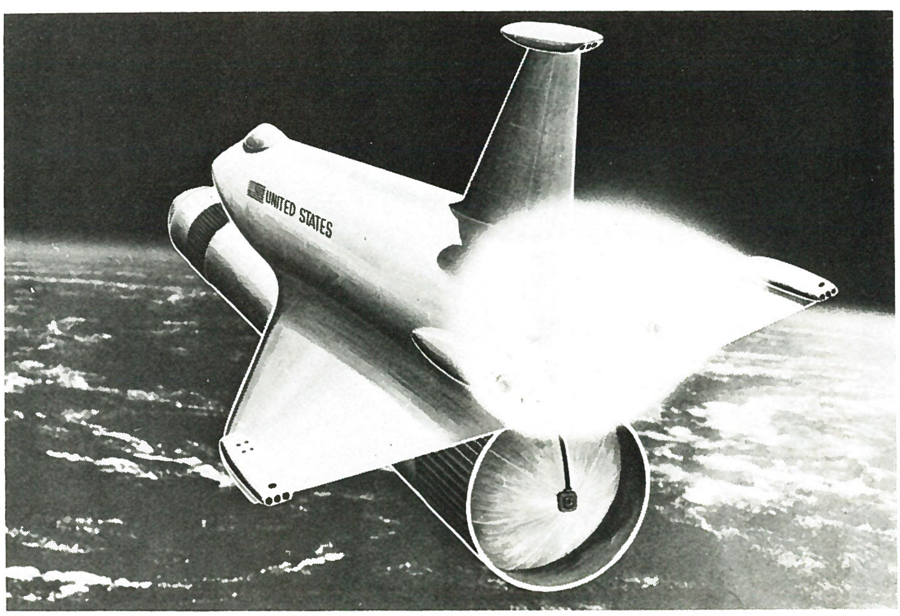

Figure 3. The selected space shuttle orbiter (see Fig. 1) with its external hydrogen/oxygen tank. The orbiter separates from its solid propellant boosters at 40 km altitude and continues on to an orbiting altitude of about 180 km, using its liquid propellant motors. The large propellant tank is then jettisoned, deorbited by retrorockets, and expended in the ocean. Auxiliary rocket motors on the wingtips are used for maneuvering during the orbital mission.

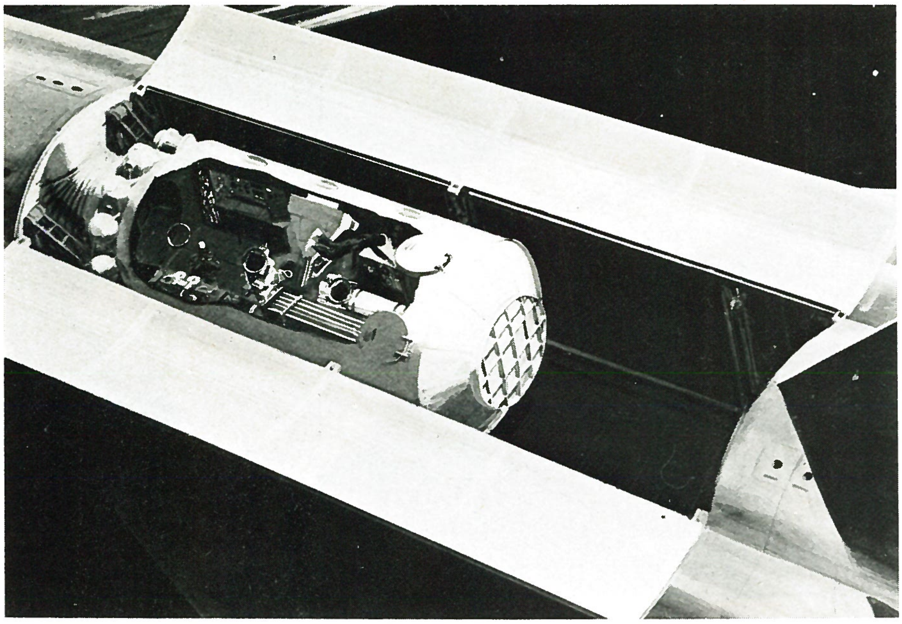

Figure 4. The sortie module concept. The preliminary sortie module, shown in cutaway form, is installed in the orbiter cargo bay. A small pressurized compartment, it can accommodate two scientists for short-duration missions.

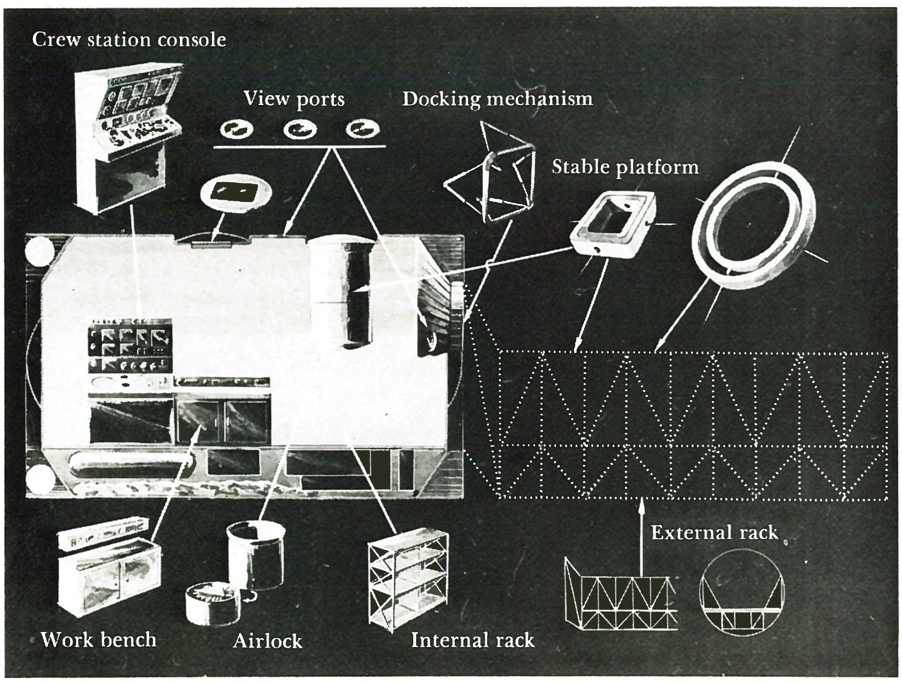

Figure 5. The sortie module, showing the different equipment that might be included for general experimentation.

and interplanetary missions into Earth parking orbits, where the shuttle will launch the spacecraft and their propulsion stages with less risk and at lower cost than with present boosters.

2. To launch and retrieve spacecraft into and from low Earth orbit. In the past 12 years or more, space operations have been retarded by long lead-times, complexity of design, high cost of payload development, and the ever-present risk of spacecraft or payload malfunction after achieving orbit. The shuttle ability to check-out in orbit or to retrieve payloads for repair, refurbishment, and re-use will relax these constraints.

3. To conduct sortie missions. NASA's research and applications modules (RAM) program is studying a family of payload carriers suitable for transport in the orbiter's cargo bay. Modules would range from a sortie lab (Fig. 4) having relatively simple laboratory equipment to more sophisticated facilities, including automated free-flyers launched and serviced by the shuttle.

The sortie lab is now being studied at the Marshall Space Flight Center, and the most desirable concept will be selected late this year; more advanced applications modules will be derived from the basic concept. The lab will be the least expensive and simplest member of the RAM family. Consisting of a small pressurized compartment, it will accommodate two scientists or experiment-support personnel in a shirt-sleeve environment for short-duration missions. A variety of different payloads and disciplines could be quickly reconfigured between missions according to special requirements. For experiments that require access to the space environment, airlocks and a pallet external to the pressurized compartment will be available (Fig. 5).

The sortie lab will therefore provide a capability at orbital altitudes and inclinations selected for particular experiments and investigations. In addition to accommodating research and applications specialists from U. S. government agencies, universities, and industry, it will also provide a practical means for international cooperation and participation in space research.

More advanced modules would have laboratories restricted to particular disciplines, such as materials science and manufacturing in space. A number of areas have been identified which offer interesting prospects (Table 1), one of the most promising being that of crystal growth. The absence of gravity and convective currents would permit the production of crystals of a purity and structure unobtainable on earth and would perhaps advance the state of the art in electronics.

In the space laboratory, it would also be possible to melt materials without physical contact, a factor important in the processing of materials which are highly reactive or which must be maintained in a very pure state. Under weightless conditions, it is expected that a material consisting of a dispersion of one solid throughout another can be manufactured. The zero gravity should make possible a more uniform dispersion of the materials, leading to higher strength or more desirable mechanical properties than can be achieved on the ground. In addition, the convective heat transfer which takes place on earth, causing circulation patterns within a melt which orient fibers or whiskers in an undesirable manner, would be absent in the space laboratory.

The weightlessness of space can be exploited in other novel ways. Pharmaceutical sera, for example, can be made much purer because convection and buoyancy can be suppressed. This may affect work in the field of genetics, which is impeded now by convection and gravity effects on fluids. New types of lenses might also be produced by cooling molten oxides into the glassy state without external disturbances that nucleate unwanted crystalline grain growth.

Free-flying modules

Free-flying modules, unlike those attached to the shuttle, would be configured for operations requiring long duration and isolation from disturbances and contamination. These modules would be automated for the most part, but would be serviced periodically by shuttle. One example of a free-flying module is the Large Space Telescope (LST), the first mission to incorporate use of the shuttle as a part of its design concept (Fig. 6). It would be transported to its proper orbit by shuttle and deployed, activated, and separated from the space craft.

Study of the LST began about seven years ago. In all of the system concepts considered, modularization at the system and subsystem level has been proposed to permit easy updating and repair in space. A major problem yet to be solved is the requirement that the LST's primary mirror, which will be approximately three meters in diameter, must not depart from its ideal figure by more than one part in a billion. The difficulty of realizing this goal is increased by the change caused by temperature variation in normal structural materials, which may be 10,000 times more than in the mirror for only one degree change in temperature. Similarly, the mirror is deformed on earth by gravitational force. However, we see the possibility of testing and measuring the mirror's configuration in a zero-gravity environment by use of the shuttle.

Other LST subsystems, such as the automatic focus and alignment, in addition to the fine pointing control, are prime candidates to be checked on a shuttle sortie mission. Early sortie missions also might include test and checkout of a light baffle. If the LST is to detect faint stars of the 28th and 29th magnitude, the problem of eliminating scattered light must be solved. Present concepts call for a tubular light baffle capable of extending in telescope fashion beyond the secondary mirror. Light entering the telescope on-axis will be focused on an imaging system behind the primary mirror. However, light entering off-axis must be attenuated so that it does not interfere with the desired beam at the focus. Special coatings on the interior of the telescope, in addition to light-capturing baffles, must be used to reduce or eliminate the stray light.

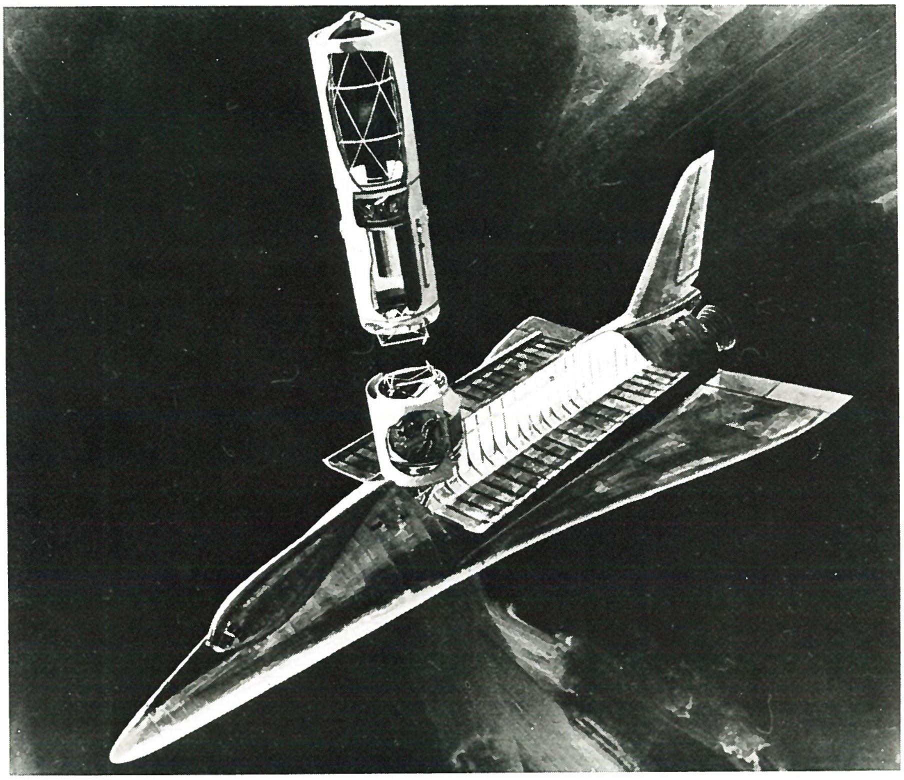

Figure 6. The Large Space Telescope is an example of a free-flying laboratory which the orbiter would place in the desired orbit and service periodically. An unmanned facility, the LST would be man-tended from time to time.

The LST, for which NASA is proceeding with detailed planning for service in the 1980s, will be available as an international facility, and it is hoped that it will encourage the global astronomical community to participate in a continual updating of the scientific instruments involved. Cost savings in the total program will be possible owing to the shuttle's capability for repair, maintenance, and updating of instruments over a period of 15 to 20 years.

In quick turn-around capability, the shuttle sortie mode will resemble present sounding rockets, which are

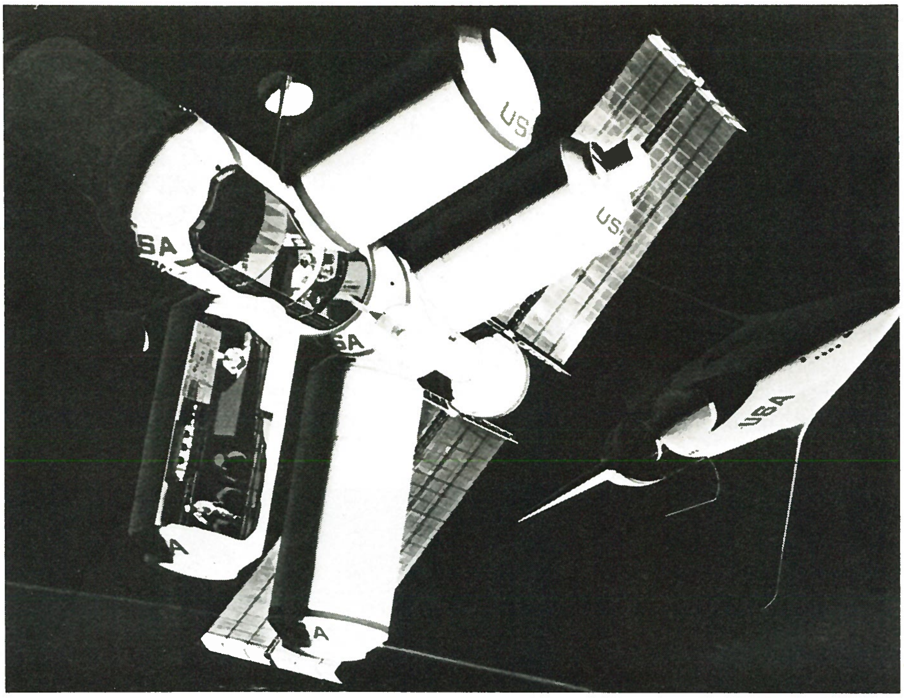

Figure 7. Modular space station core to which laboratory modules are transported and semipermanently docked by shuttle.

Table 1. The technical areas in materials science and manufacturing that NASA has identified for possible exploitation in shuttle missions.

1. *Crystal growth*
   Crystal growth from convectionless solutions and vapors
   Crystal growth from melt, shaped for final use
   Floating zone refining
2. *Metallurgical processes*
   Metal matrix composites
   Eutectic and monotectic alloys of controlled structures
   Foam casting
3. *Biological preparations*
   Electrophoretic purification of vaccines
   Incubation processes for biologicals
4. *Glass preparation and processing glasses*
   Produced by containerless solidification
   High-quality lenses for lasers and optical instruments
5. *Physical processes in fluids*
6. *Chemical processes in fluids*

launched to altitudes ranging from 50 to about 1,000 miles and then fall back to earth. It will not, however, have the severe restrictions these rockets place on observation time, nor will it be necessary to automate the instruments. For example, we discovered pulsating X-rays with Explorer 42, but the sensors and electronics on board do not permit detailed measurements of time variations. If the shuttle were available, this problem could be solved within a few months. As it is, we must await the Small Astronomy Satellite, scheduled for 1974, as the earliest opportunity at which these pulsating sources can be studied further.

In addition to quick follow-up investigations, the shuttle will aid in developing new instruments. The principal investigator can evaluate his data as they are obtained and explore various instrument parameters. In many instances, shuttle sortie flight duration, ranging from a few hours up to a week, will be adequate to complete most experiments. If longer investigations are necessary, new instruments may be flown in a shuttle-launched satellite. We have already identified candidate instrument payloads for sortie flights not only for infrared and X-ray astronomy but also for plasma physics, high energy cosmic rays, and optical astronomy.

Other modular payload carriers will evolve in capability and sophistication according to requirements of the user community and the availability of funds. Possibly a final step in the evolution of Research and Application Modules will be a space station assembled in orbit (Fig. 7). Definition studies were completed last year and preliminary space station designs were developed by North American Rockwell and McDonnell-Douglas. All elements would be sized for compatibility with the shuttle's cargo bay of 4.5 m diameter and 18 m length. Initial capacity of the station would be six persons, with the option of expanding later to twelve when the need and funds permit. This class of station would provide an extensive capability of conducting multidisciplinary experiments with the principal investigators on board when required. The shuttle would provide logistics supply and personnel transfer to and from the space station and ground base.

An important factor in the shuttle

design concept is its growth potential. The configuration now planned is limited to near-earth operations; however, the same concept could be adapted to a logistics transport connecting orbiting earth and lunar stations and carrying personnel and supplies. NASA, of course, has no plans for manned lunar shuttle flights. In the event, perhaps in the 1980s or '90s, that we should want a permanent scientific lunar base, shuttle technology could be developed to provide logistics support between earth and moon.

In our unmanned planetary programs, the shuttle is expected to increase the range and scope of missions, with the aid of a high-energy upper stage during the 1980s. While planetary missions require extremely high launch energies, which the shuttle alone cannot supply, a combination of space shuttle and high-energy stage could meet the requirement. Called a "space tug," this additional stage would be designed to be reused many times in launching planetary missions from orbit. An early tug capability is possible using existing hardware such as the Agena Centaur. However, sophisticated tug development must wait until peak funding on the shuttle has been passed, in order to maintain our stable budget plan.

In the meantime, studies are being made of the most feasible high-energy upper stage that will integrate into the shuttle. Among candidate concepts are a small nuclear rocket, solar electric propulsion, nuclear electric propulsion, and advanced chemical rockets. A combination of shuttle and small nuclear rocket systems could reduce trip times significantly for outer planet missions.

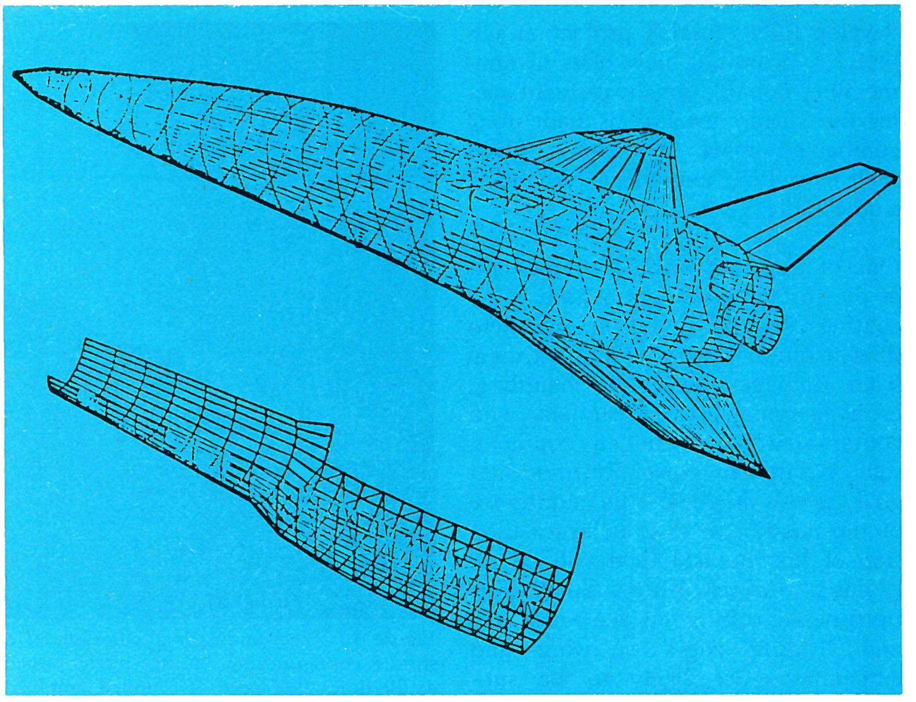

Figure 8. Structural design computer methods, such as NASA Structural Analysis (NASTRAN), permit the analysis of complex structures. Auxiliary computer routines automatically generate input data for the program. For example, user-prepared input for generating hypothetical orbiter configuration and the finite-element model of a fuselage structure segment require less than one man-day to prepare from engineering drawings. Conventional methods require a month.

Design considerations

In mating the space rocket vehicle with the airplane, which the winged orbiter represents, we have created some novel technical problems. Basically, we must construct an aerospace frame that will survive repeated severe atmospheric reentry conditions and, at the same time, remain within weight limits required if the vehicle is to be economical and capable of performing its design objectives.

The shuttle's demanding performance requirements and the severe multiple environment exposure make it mandatory to apply very accurate and comprehensive analytical tools in structural design. Design technology, therefore, will be advanced by use of large-scale, versatile computers. For example, computer methods, such as the NASA Structural Analysis (NASTRAN), now permit analyzing complex structures with more than 40,000 mathematical degrees of freedom—in marked contrast to the 3 to 6 degrees of freedom used when calculations were made manually. These computers and associated software also permit study of the dynamic, or vibrational, characteristics of the structure as well and thus are doubly effective in projecting design loads and dynamic effects.

Minimizing the cost and time required for the design procedures is emphasized. Auxiliary computer routines, such as those already developed at our Langley center, will automatically generate the input data for the NASTRAN program. For example, the user-prepared input for generating a hypothetical orbiter configuration (Fig. 8) and the finite-element model of a segment of the fuselage structure required less than one man-day to prepare from drawings. This contrasts with the month needed for hand-generated input.

Although aluminum has been chosen as the basic construction material for the current shuttle design, NASA is investigating a method of fiber reinforcement of structural elements to reduce structural mass. Boron or carbon fibers can be produced with extremely high strength-to-weight ratios. By attaching these fibers to a structural web, or moulding them into the metal itself, we can reduce the mass by as much as 15 percent with no sacrifice in load-carrying ability. Applications to skin panels, fuselage frames, thrust-structure shear webs, and landing gear doors are being studied. However, before taking this step, we must establish the fatigue and life characteristics of such structures over the air-frame's useful life.

Another extremely important part of the work on structures and materials is the development of suitable materials to withstand the elevated temperatures experienced by vehicle surfaces during reentry into the atmosphere. These temperatures are as high as 1,650°C. Ablative materials, which in the past have been used for thermal protection of all reentry spacecraft, do not have the potential for reuse needed for the shuttle, although we may use them on initial flights and thus provide more time to develop fully reusable protection systems. A promising new class of nonmetallic, nonablating heat-shield materials—surface insulations made up of compacted mats of ceramic fibers such as mullite and silica—are being studied (Fig. 9).

One of the most critical components of the surface insulation system is the coating which must seal the absorbent fibers from moisture and protect them from damage caused by handling, erosion, impact, and reactions with contaminants in the environment, such as salt. An especially important goal is to increase the emittance of the coating so that a larger fraction of the incident heat will be reradiated during reentry. Small portions of the orbiter surface—nose cap and leading edges of wing and empennage—are likely to be subjected to temperatures of 1,650°C, which are beyond the projected capability of the reusable surface insulators. Coated carbon materials would be an improvement over ablators because they hold a potential for reuse.

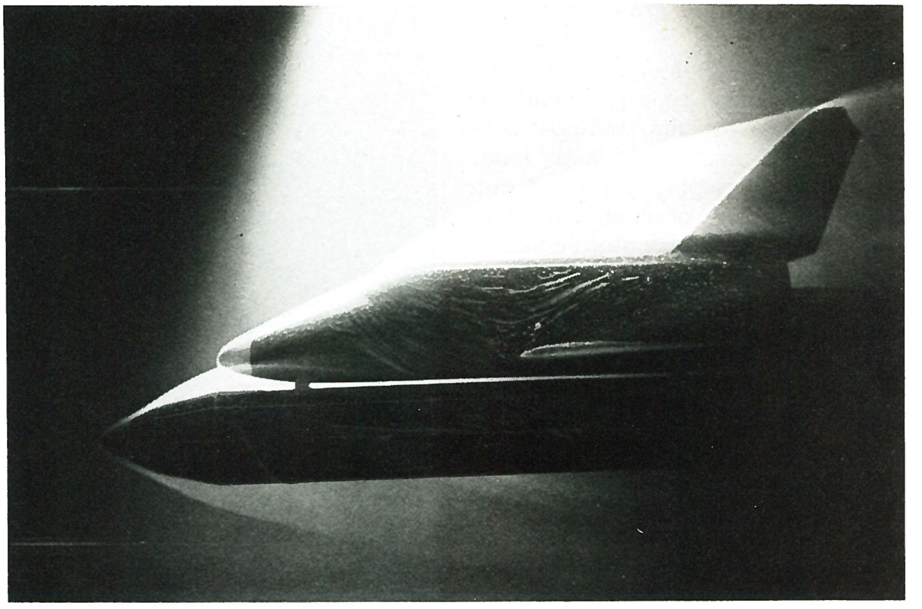

Figure 10. Electron-beam photograph of a shuttle configuration. Shuttle model tested at 20 times the speed of sound. Combined electron beam illumination and phase-change paint are used in the test. The electron beam illuminates shock patterns, and motion pictures indicate relative heating rates through changes in temperature-sensitive paint. Streaks on the model indicate the direction of the stream flow at the surface.

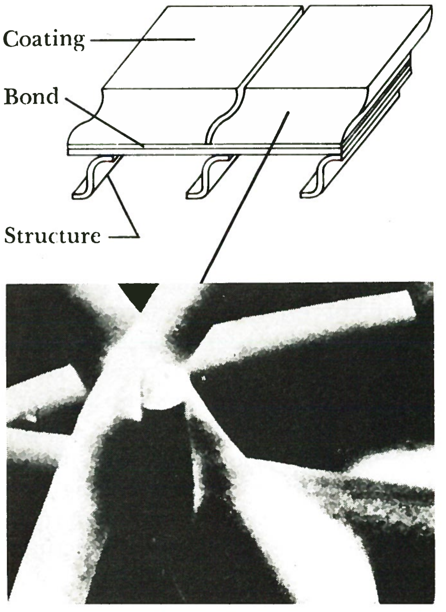

Figure 9. The reusable surface insulation required for the orbiter is being researched among nonmetallic, nonablating materials. It is made up of mats of compacted ceramic fibers such as millite and silica. Because these materials are inert and retain their strength at temperatures predicted for the greater part of the orbiter's surfaces, they have a potential of many reuses. If brought to a satisfactory state, surface insulators offer a potential for both a stable heat-resistant aerodynamic surface and thermal insulation of the basic structure. They also appear to be applicable to major portions of the shuttle orbiter. Current research focuses on improvements necessary to realize the concept's full potential.

Flight characteristics and aeroheating effects of candidate orbiter and booster designs, both mated and separate, are being investigated across the entire speed spectrum from launch through hypersonic reentry and back to subsonic landing speeds. Data include local heating effects caused by shock formation and impingement, flow interference and vortex formation, and detailed criteria for adequate flight-handling qualities of the vehicles. Test data are reduced to a standard format and reported to all NASA and contractor personnel by a computerized system. Extremely rapid methods are employed for determining heat-transfer effects at hypersonic velocities (Fig. 10). A combined electron beam illumination and phase-change paint test discloses the shock patterns, and motion pictures indicate the relative heating rates through changes in the temperature-sensitive paint.

The complex field of vehicle dynamics and aeroelasticity is concerned with the transient and oscillatory behavior of the large, flexible vehicle system in response to loads and aerodynamic disturbances. Dynamic behavior involves the interaction of the entire vehicle system: its structure, skin, propulsion units, and controls, whether electronic, mechanical, or aerodynamic (Fig. 11). Adverse coupling of these elements can amplify stresses and necessitate increases in structural mass.

Fatigue-life study results are fed back into the structural design, and, as configurations are selected, vehicle size and weight estimates refined, and weight distribution established, the various possible modes of oscillation—including the shapes of structural deformation, oscillatory frequencies, and possible dynamic amplification of loads and stresses—will be determined. A computer analyzes the oscillatory vehicle motions, converts them into diagrams, and displays them in rapid sequence on an oscilloscope tube for visual recognition of the troublesome modes. Particularly critical is the suppression of longitudinal oscillations resulting from coupling of engine thrust, propellant motion in feedlines, and vehicle structural deformation.

Propulsion systems

Propulsion systems and their propellants comprise the major part of the shuttle vehicle mass, and the capabilities of these systems, therefore, virtually define the capability of the vehicle. Our work is directed at the technology of the booster engines, the auxiliary propulsion and orbital maneuvering engines, and the auxiliary power units for the shuttle. The main propulsion engines for the orbiter are based on the advanced technology developed under Air Force and NASA programs for high pressure liquid hydrogen/oxygen systems. With the orbiter/booster configuration now considered, the booster main engines will be of a type totally different from those in the orbiter. The first shuttle will use solid-propellant booster engines, for which adequate technology exists. Eventually, the fully reusable shuttle will use liquid-propellant motors, but the solid-propellant type is considered best for our present, more limited purposes.

Shuttle requirements for auxiliary propulsion for maneuverability in space are unique in our experience. The rocket engines will be more powerful than those used in Apollo. Levels in the range of 2,200 to 4,450 newtons will be required of each multiple thruster, and these thrusters must each have rapid responses and precisely controlled firing duration. To achieve the reliability and operational economy commensurate with shuttle requirements, an operating life of hundreds of thousands of thrust cycles with nearly zero maintenance is necessary. The thrusters will be mounted in pods at the wingtips and in the nose section of the orbiter, and they will burn earth-storable propellants, either a monopropellant or hypergolic bipropellants. While the basic technology for these propellants exists, systems of adequate size, reusability, and recycling capabilities have not been demonstrated. In particular, engine chambers of long-life capability, improved controls, and long-life seals and valves must be investigated.

For auxiliary power, two electrical power units are under study: a turbine-driven unit to supply the peak power needed during launch, reentry, and landing, and fuel cells to provide the steady-state moderate power demands for the orbiter. The preferred concept for the turbine-driven auxiliary power unit has been defined for hydrogen/oxygen propellants. To reduce system complexity and cost, a monopropellant fuel may be selected. Further work is therefore needed on the design, evaluation, and demonstration of major system components of a monopropellant power system for this 200–400 hp unit.

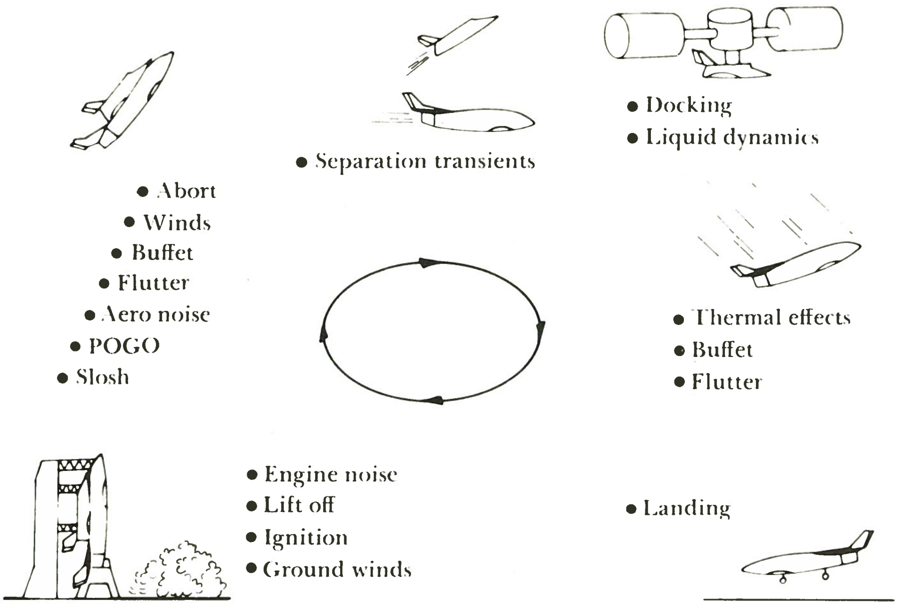

Figure 11. Vehicle dynamics and aeroelasticity is a complex discipline concerning the transient and oscillatory behavior of a large, flexible vehicle in response to loads and aerodynamic disturbances. Dynamic behavior involves interaction of the entire vehicle system: structure, skin, propulsion units, and controls. The suppression of POGO oscillation (longitudinal oscillations resulting from coupling of engine thrust, propellant motion in feedlines, and vehicle structural deformations) is especially critical. "Slosh" is the back-and-forth movement of liquid fuel in the tanks. 100 mission cycles of the type illustrated are projected for the orbiter.

Power and control systems

Fuel cells for the orbiter's continuous power application will use hydrogen and oxygen and will convert the energy of these propellants electrochemically. This is considered more efficient than thermomechanical conversion. For long-term operations, the resulting low fuel consumption will provide a significant advantage compared with the turbine-driven unit. However, fuel cells are limited in power output. The useful life of the Apollo fuel cell is significantly less than that desired for the shuttle, and NASA is therefore aiming at an order-of-magnitude increase in useful life of such cells. The work will be directed principally in the areas of improved catalysts, electrode structure, cell material, and auxiliary components.

Returning from a mission, the orbiter must make an unpowered descent and land at conventional airport facilities. Since its basic handling qualities and flight characteristics will limit maneuverability and rule out a second pass at the landing field, this objective places severe requirements on the orbiter navigation and flight control systems. A flight evaluation program on a research airplane equipped with laboratory avionics representative of the shuttle systems will be conducted at Ames Research Center, Calif.

The shuttle mission also requires various instruments that are accurate, sensitive, reproducible, reliable, and compatible with the different velocity regimes, environmental conditions, and operational requirements of the vehicle. Among these is a gauge for measuring liquid fuels under zero-gravity conditions. Two methods that appear suitable for the shuttle are a nuclear-absorption technique and a radio-frequency technique (Fig. 12). The nuclear absorption method depends upon the gamma-ray absorption characteristics of the fuel when gamma-ray sources are placed on one side of the tank and detectors on the other. The other technique relies on the fundamental relationships between propellant mass and standing wave mode counts. Both these techniques will be investigated to determine which offers the greatest advantages.

Program efforts in biotechnology have generally stressed those system elements in which the shuttle environment and operations differ from those applicable in Mercury, Gemini, Apollo, and Skylab. Although most of the constraints in these earlier programs will not be exceeded in the shuttle, some new approaches and equipment are needed. The combination of space operations with longer durations of flight in the atmo-

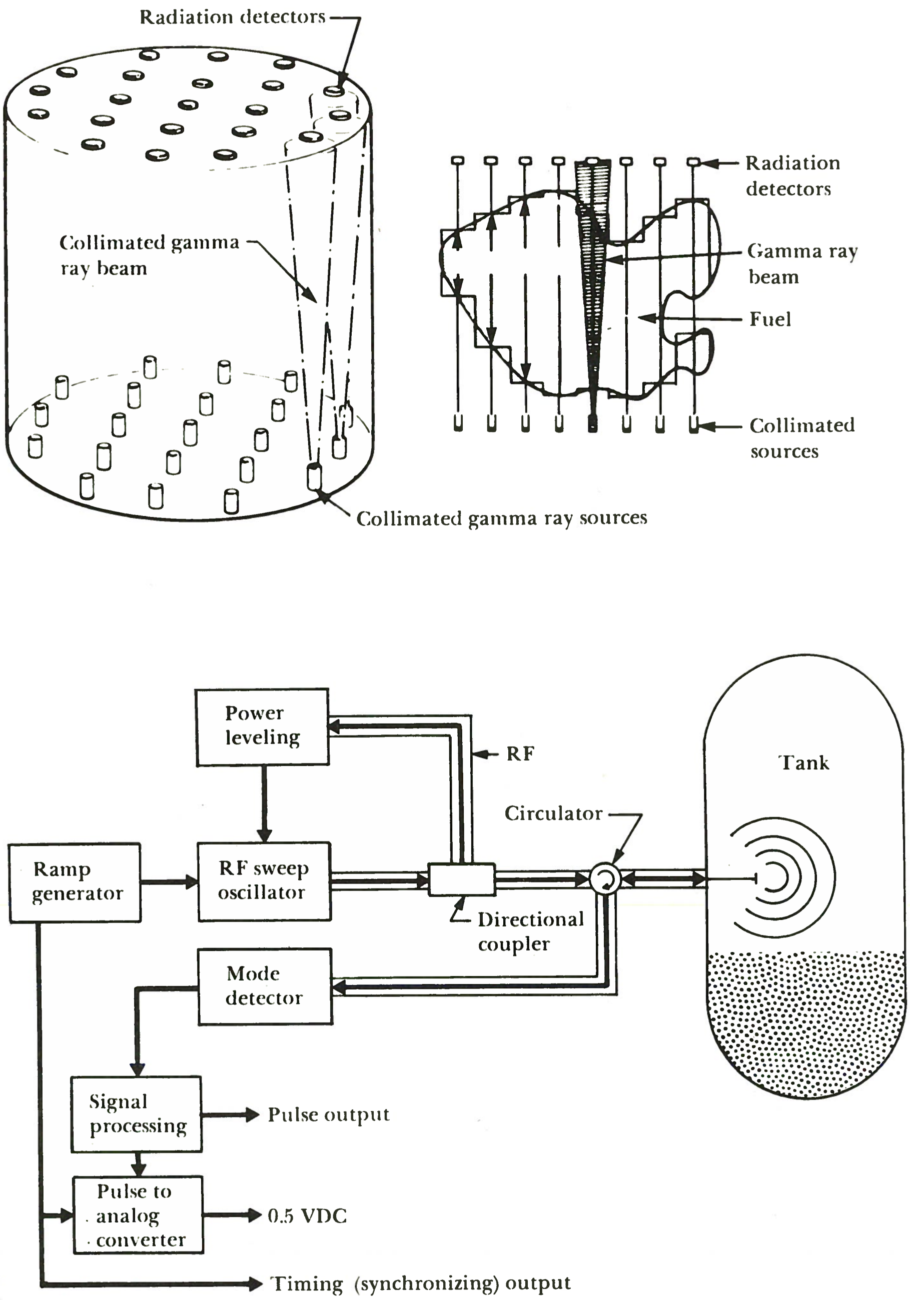

Figure 12. Liquid-fuel gauging methods that are being studied for zero-gravity conditions include (*top*) the nuclear absorption technique and (*bottom*) the radio-frequency mode counting system. In the nuclear absorption method, gamma-ray sources are placed on one side of the tank and detectors on the other. The radio-frequency mode relies on basic relationships between propellant mass and standing wave mode counts.

sphere, the use of highly trained crews and relatively unconditioned technical personnel, and extreme systems flexibility required for missions varying from a crew of 2 for short times to as many as 10 for longer durations, pose unusual conditions.

New approaches are being developed for sensors and regenerative controllers for humidity and carbon dioxide; improved waste management, collection, and storage; mechanical refrigeration systems; flash evaporators; and cryogenic cooling heat exchangers. The improved equipment will reduce cost and improve performance, reliability, maintenance, and safety. Studies also are in progress to establish visibility and display requirements for approach and landing. These will be used, together with vehicle characteristics and other inputs, to define a full mission simulator for crew training and evaluation of crew performance through realistic simulation of all flight phases.

The major risk areas are the thermal protection system and the weight problem. Since the 1950s, considerable work has been done by the Air Force, industry, and NASA, beginning with early space plane studies, Dyna-Soar, the aerospace plane, continuing through space shuttle design and development studies. With this background we can be confident of producing a vehicle within cost limits that will be a major advance in space flight technology. The shuttle offers broad access to space at significantly lower cost than is possible by existing vehicles. Its versatility will open new avenues of opportunity for space science and the utilization of space that are far beyond our capabilities today.